Development and Application of an Indoor Air Quality Commissioning Program in a New Office Building

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ABSTRACT

An indoor air quality commissioning program has been developed and is being implemented in a new office building in Rockville, Maryland. New buildings can have an increased potential for indoor air quality (IAQ) problems due to new building materials and deficiencies in mechanical ventilation system operation during construction and initial occupancy. This IAQ commissioning effort is being implemented to reduce the potential for such problems in this building. This commissioning program consists of three tasks: (1) evaluate the mechanical ventilation system design, (2) develop a set of criteria that will be used to evaluate IAQ in the building, and (3) measure various environmental parameters for comparison with the criteria developed in task 2. Tasks 1 and 2 have been completed and task 3 is in progress. The evaluation of the mechanical ventilation system design was based on the recommendations of ASHRAE Standard 62-1989 and the 1987 BOCA mechanical code. The design evaluation showed that the system ventilation rates were consistent with the recommendations of the ASHRAE standard and the requirements of the BOCA code. The IAQ criteria developed in task 2 address ventilation system performance, indoor pollutant levels, and thermal comfort. These criteria are based on appropriate standards and guidelines and on the results of previous IAQ research. Task 3 consists of the measurement of these IAQ parameters in three phases of building construction: after completion of interior buildout, after the installation of the systems furniture, and roughly one month after occupancy. The first phase of task 3 is complete and the results indicate compliance with the IAQ criteria prior to installation of the systems furniture.

INTRODUCTION

Building commissioning generally refers to the process of verifying that building mechanical systems are operating as designed (ASHRAE 1989a). A typical commissioning program includes the testing and balancing of air- and water-handling systems, verifying the operation of heating and air-conditioning units, and testing building control systems along with other mechanical systems. Commissioning generally does not include the verification of an "acceptable" indoor environment for the building occupants, including factors related to indoor air quality (IAQ). In light of growing concern about indoor air quality, IAQ commissioning could become an important part of building commissioning programs, provide a safe and comfortable working environment for the building occupants, and reduce other problems related to building operation. There are currently no standard IAQ commissioning programs. Efforts to date have ranged from limited pre- and post-occupancy surveys to long-term monitoring efforts involving elaborate installations of instrumentation (Sterling et al. 1992; Grot et al. 1989; Persily et al. 1992).

In order to identify and understand the issues involved in developing and implementing such a program, a pilot IAQ commissioning program has been developed and is currently being applied to a new office building in Rockville, Maryland. This commissioning program is not presented as a candidate protocol for IAQ commissioning. Instead, it should be viewed as a pilot program that will assist in the development of reliable and cost-effective IAQ commissioning protocols. The program described in this paper consists of three tasks: (1) evaluate the mechanical ventilation system design from an indoor air quality perspective, (2) develop a set of parameters and associated criteria that will be used to evaluate IAQ in the building, and (3) measure these environmental parameters in the building for comparison with the criteria developed in task 2. Tasks 1 and 2 have been completed and task 3 is in progress. This paper describes the tasks and presents the results that are available.

In task 1, the ventilation system design was compared to the 1987 BOCA National Mechanical Code (BOCA 1987), to which the building's mechanical systems were designed. In addition, the design was compared to ASHRAE Standard 62-1989 (ASHRAE 1989b). In task 2, a set of IAQ parameters was selected based on a review of standards, guidelines, and research literature. In task 3, the IAQ parameters are being measured in three phases of building construction:

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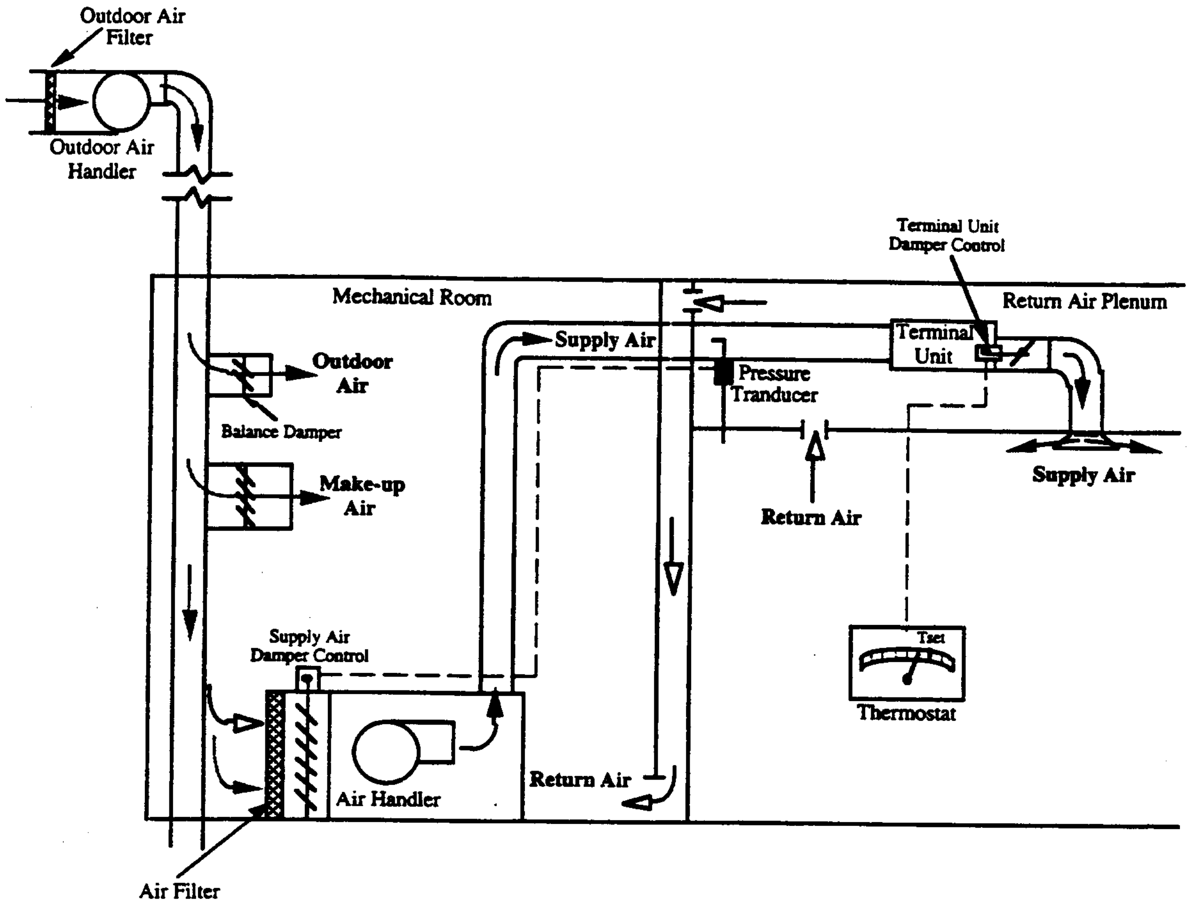

Figure 1 Schematic of ventilation system.

interior buildout complete, wall and furniture systems installed, and approximately one month after occupancy. The interior buildout consisted of interior framing and sheetrock, painting the sheetrock, and installation of ductwork, dropped ceilings, lighting, and carpet. The wall systems installed prior to phase 2 testing are modular floor-to-ceiling partitions used to form individual offices and conference facilities. The systems furniture consists of office cubicles separated by fabric-covered partitions approximately 2 m (6 ft) high furnished with modular office equipment. The first phase of task 3 is complete and the results of these measurements are presented in this paper.

Building and Ventilation System Description

The building has 10 floors above grade (levels 1 through 10), 4 below grade (levels P1 through P4), and a penthouse level that houses the mechanical systems. Floors 2 through 10 consist primarily of open office space that is divided into workstations by the office systems furniture. The main entrance to the building is on level 1, along with the cafeteria, exercise facility, employee credit union, and an exhibit area. Level P1 is below grade in the front of the building and above grade in the rear and consists of a daycare center and part of the parking garage. A two-story auditorium is located on level P2 and extends up to level P1. The parking garage extends from level P1 to level P4. There are three core areas in the building—the elevators in the center of the building and two stairwells at opposite ends of the building.

The building has variable-air-volume (VAV) air handlers with constant outdoor air intake rates. Two outdoor air intake fans on the roof provide outdoor air to all of the building's air handlers except the auditorium air handler, which has a ground-level outdoor air intake. The flow rates of these fans were set during the testing, adjusting, and balancing of the ventilation system to provide the design outdoor airflow rate. There is no provision to control these outdoor airflow rates because the VAV ventilation systems modulate supply airflow rates. Two mechanical rooms are located on each of levels 2 through 10, and each mechanical room contains a supply air handler that serves one side of the floor. Other air handlers serve the first-floor lobby, daycare center, auditorium, and other areas of the building. There are exhaust fans for the restrooms, garage, and other areas such as janitorial closets, and for smoke control.

Figure 1 is a schematic of an air-handling system for a typical floor. The major components include the outdoor air intake fans on the roof, the mechanical room, the air handler, the terminal units or VAV boxes, the supply air diffusers,

TABLE 1
Design Airflow Rates

Air Handler Number	Design Airflow Rates [L/s]		Location Served	Floor Area [m^2]	Design or Estimated Occupancy	Outdoor Airflow Rate				
						[$L/s/m^2$]		[L/s per person]		
	Supply	Outdoor				Design	ASHRAE	Design	ASHRAE	BOCA
Supply Air Handlers										
A-1	5,192	708	Level A - Daycare	790	100 †	-	-	7	8	2
A-2	1,133	94	Level A - Storage and Hallway	186	-	0.51	0.25	-	-	2
A-3	1,558	189	Level 1 - Main Entrance Lobby	297	-	0.63	0.25	-	-	2
A-4	566	566	Level A - Elevator Lobby	46	-	12.19	0.25	-	-	2
AT-1	5,492	1,628	Level B - Auditorium	517	310	-	-	5	8	2
2T-1	2,336	295	Level 2 - Fitness Area	437	72 ††	-	-	4	10	5
2T-2	2,053	673	Level 2 - Meeting Room	177	110	-	-	6	10	4
2T-3	1,109	366	Level 2 - Subcommittee Room	74	64	-	-	6	10	4
3T-1	661	142	Level 3 - Learning Center	116	26	-	-	5	8	2
AHU 2-1	8,874	779	Level 2 - North	3,033	86	-	-	18	10	2
AHU 2-2	8,874	779	Level 2 - South			-	-			
AHU 3-1	8,874	779	Level 3 - North	3,033	89	-	-	18	10	2
AHU 3-2	8,874	779	Level 3 - South			-	-			
AHU 4-1T	12,272	1,605	Level 4 - North	3,033	144	-	-	22	10	2
AHU 4-2T	12,272	1,605	Level 4 - South			-	-			
AHU 5-1	8,874	779	Level 5 - North	3,033	85	-	-	18	10	2
AHU 5-2	8,874	779	Level 5 - South			-	-			
AHU 6-1	8,874	779	Level 6 - North	3,033	181	-	-	9	10	2
AHU 6-2	8,874	779	Level 6 - South			-	-			
AHU 7-1	8,874	779	Level 7 - North	3,033	184	-	-	8	10	2
AHU 7-2	8,874	779	Level 7 - South			-	-			
AHU 8-1	8,874	779	Level 8 - North	3,033	205	-	-	8	10	2
AHU 8-2	8,874	779	Level 8 - South			-	-			
AHU 9-1	8,874	779	Level 9 - North	3,010	199	-	-	8	10	2
AHU 9-2	8,874	779	Level 9 - South			-	-			
AHU 10-1	8,874	779	Level 10 - North	3,010	193	-	-	8	10	2
AHU 10-2	8,874	779	Level 10 - South			-	-			
TOTAL	186,622	20,331		29,893	2,048	0.68		10	10	5
Outdoor Air Handlers										
OA/MAF-PH-1&2		22,609	The Entire Building	29,893	2,048	0.76	-	11		

† Maximum occupancy
†† Estimated occupant density based on ASHRAE Standard 62-1989 for gymnasiums = 30 people/100 m^2

and the thermostats associated with the terminal units. Under the occupied mode of operation, the two outdoor air intake fans are designed to provide a constant outdoor airflow rate to each mechanical room, based on a one-time setting of balance dampers in each mechanical room. Therefore, there is no automated control of the outdoor airflow rate for each air handler as the supply airflow rate varies. Outdoor air and return air mix inside the mechanical room to make up the supply air to be delivered to the occupied space of the building. A set of make-up air dampers in each mechanical room remains closed under normal occupied conditions and provides make-up air to be used for smoke control in the event of a fire. The supply air is conditioned at the air handler to a temperature of approximately 7°C (45°F). The ventilation system is a cold-air distribution system as opposed to most commercial building ventilation systems, which have a supply air temperature of about 13°C (55°F). With the exception of the fourth-floor air handlers, there are no humidification systems in the building's air handlers.

TASK 1—EVALUATION OF THE VENTILATION SYSTEM DESIGN

Ventilation System Design Codes and Standards

The evaluation of the ventilation system design was based on mechanical drawings and specifications for the base building and mechanical, architectural, and space-use drawings for the interior buildout. The design ventilation rates were based on the 1987 BOCA National Mechanical Code, which contains minimum ventilation requirements based on the occupancy of a room. These requirements include minimum amounts of supply air per person or per floor area, depending on the type of space and maximum allowable recirculation rates. Up to two-thirds of the supply air may be recirculated return air if particulate levels in the supply air are less than those specified in Table M-1603.2.1 of the code. Up to 85% of the supply air may be recirculated if filtering or absorption equipment is used that maintains the supply air within additional contaminant limits in the code. However, the outdoor air quantity shall not be less than 2.4 L/s (5 cfm) per person. The BOCA code also requires that restrooms be ventilated by one of several methods, with 12 L/s (25 cfm) of supply air per water closet or urinal. Assuming one-third outdoor air in the supply air, 4 L/s (8.3 cfm) of outdoor air are required per water closet or urinal. BOCA also requires that the exhaust airflow rate be greater than or equal to the design supply airflow capacity for the restroom.

The ventilation system design was also compared to ASHRAE Standard 62-1989. While the building was not specifically designed to conform with Standard 62-1989, this standard is gaining wide acceptance as a basis for designing buildings to achieve acceptable IAQ. The standard contains two procedures that can be used to achieve acceptable IAQ—the indoor air quality procedure and the ventilation rate procedure. The latter procedure was used to evaluate the ventilation system design of this building. The ventilation rate procedure contains a minimum outdoor airflow rate of 10 L/s per person (20 cfm/person) for office space and a minimum outdoor airflow rate of 25 L/s (50 cfm) per water closet for public restrooms. Standard 62-1989 also recommends the provision of mechanical exhaust from restrooms with no recirculation of the exhausted air back into the building, although it does not provide recommended exhaust airflow rates.

Comparison of Ventilation System Design vs. Codes and Standards

Table 1 lists the main air-handler numbers, their design supply airflow capacities and outdoor airflow rates, the space served by the air handler, the floor area and design or estimated occupancy of each space, and the minimum outdoor airflow rates based on the 1987 BOCA National Mechanical Code and ASHRAE Standard 62-1989. The design occupancies for the spaces shown in Table 1 are based on the space plan drawings for each floor, with the exception of the fitness area. The occupancy for the fitness area is based on the estimated occupant density for gymnasiums given in ASHRAE Standard 62. For this zone, the occupancy is based on the floor area, which is occupied under "normal use conditions." Recommended outdoor airflow rates are given in units of flow rate per person or unit floor area, depending on the type of space.

The design ventilation rates of all spaces listed in Table 1 exceed the ventilation rates required by the BOCA Mechanical Code with the exception of the fitness area. However, the design occupancy in Table 1 for the fitness area is an estimate, and therefore the discrepancy between the design and the code may not be significant. The design outdoor airflow rates for levels 2 through 10, with the exception of level 4, are all the same independent of the number of occupants designated for the zones. Level 4 has a higher design outdoor airflow rate than the other floors, even though the number of occupants is less than those of levels 6 through 10. There are no estimated occupant densities for hallways, entrances, or lobbies in either the BOCA code or ASHRAE Standard 62-1989. Therefore, design outdoor airflow rates per person could not be calculated for the level A storage and hallway, main entrance lobby, and elevator lobby. However, the design outdoor air intake rate for these zones can be compared with the ASHRAE recommendation in units of L/s per m^2 of floor area (cfm/ft^2). For the first two spaces, the design value is roughly two times the ASHRAE minimum outdoor air requirement. For the elevator lobby, the design value is almost 50 times the ASHRAE minimum.

While the building was not designed to ASHRAE Standard 62-1989, some of the design values are slightly below the minimum outdoor airflow rates recommended in the standard. These differences exist on levels 6 through 10, which have design values that are between 5% and 20% less than ASHRAE-recommended levels of outdoor airflow rate. These levels are mostly made up of open office space and have some of the highest occupancies in the building. Outdoor airflow rates to levels 2 through 5 are much higher than the ASHRAE-recommended levels. The design outdoor airflow rate for the daycare center is just below the ASHRAE recommendation for classrooms, while the auditorium, fitness center, level 2 meeting room, and learning center have design outdoor airflow rates between 25% and 50% below the levels recommended in ASHRAE Standard 62-1989. Based on the total design occupancy and the capacity of the outdoor air intake fan (the last entry in Table 1), the design outdoor airflow rate for the entire building is approximately 11 L/s per person (23 cfm per person). These comparisons between the design outdoor airflow rates and the BOCA and ASHRAE requirements are all made for the spaces served by each individual air handler and do not address the important issue of the adequacy of outdoor air delivery to individual rooms and workstations.

Exhaust and ventilation air requirements for the main restrooms on levels 2 through 10 were compared to the BOCA and ASHRAE standards. The design exhaust flow rate is 283 L/s (600 cfm) for each restroom. Based on the number of water closets in each restroom, the design exhaust rates are 57 L/s (120 cfm) and 71 L/s (150 cfm) per water closet for the men's and ladies' restrooms, respectively. Each restroom has a design supply airflow rate of 47 L/s (100 cfm), which translates to an outdoor airflow rate of 0.9 L/s (2.0 cfm) and 1.2 L/s (2.5 cfm) per water closet for the men's and ladies' restrooms, respectively, based on the ratio of design outdoor air to supply air (about 10%). As required by BOCA, the design exhaust rates are greater than the design supply airflow rate. While the design outdoor airflow rates for the restrooms are lower than the BOCA and ASHRAE requirements, transfer ducts connect the return air plenum above the ceiling in the office area to each restroom and provide "make-up" air to the restrooms. Assuming a total airflow rate to the restrooms consisting of supply air and transfer air that is equal to the exhaust airflow rate of 283 L/s (600 cfm) and assuming 10% outdoor air in the supply air, the outdoor airflow rate is approximately 5.7 L/s (12 cfm) and 7 L/s (15 cfm) per water closet for the men's and ladies' rooms, respectively. These values are higher than the 4 L/s (8.3 cfm) per water closet required by BOCA and less than the outdoor airflow rate of 25 L/s (50 cfm) per water closet in ASHRAE Standard 62-1989.

The BOCA code allows return air recirculation if the particulate levels in the ventilation air are kept below a specific limit and increased recirculation if the levels of other pollutants are kept below additional limits. The ASHRAE standard requires an analysis of outdoor pollutant levels and the use of air cleaning if the outdoor levels exceed limits specified in the standard. The building design documentation reviewed by the authors does not discuss assumed pollutant levels in the ventilation or outdoor air or the use of filtration or air cleaning in relation to the recirculation of return air.

TASK 2—IAQ CRITERIA

Three categories of IAQ parameters are being measured in the building during task 3 of the project: ventilation performance, pollutants, and thermal comfort. The following is a list of all the IAQ parameters:

Ventilation Performance	Pollutants	Thermal Comfort
Outdoor Airflow Rate	Carbon Dioxide	Temperature
Relative Pressurization between Zones	Carbon Monoxide	Relative Humidity
	Formaldehyde	Operative Temperature
	Particulates	
	Radon	
	Volatile Organic Compounds	

In order to implement the commissioning program, criteria were developed during task 2 to which the measured values of each of these parameters will be compared. The following sections discuss existing criteria, other parameters, and the specific criteria used in this project. The project criteria were based on the existing criteria, other IAQ research findings, and resources available for the study. The criteria are being used as points of reference for comparing the pollutant measurements in this building. They provide a broad assessment of IAQ conditions and do not include every pollutant that can impact occupant health and comfort. Also, they are based on the limitations that currently exist in the understanding of factors that impact indoor air quality.

Ventilation Performance

Outdoor Airflow Rate The outdoor air ventilation requirements of the BOCA National Mechanical Code and the ventilation rate procedure of ASHRAE Standard 62-1989 were both described earlier. The BOCA code contains a minimum outdoor air intake rate of 2.5 L/s (5 cfm) per person and other outdoor air requirements, depending on the type of space. The minimum ventilation rate of 10 L/s (20 cfm) per person required for office space, given in ASHRAE Standard 62-1989, was selected as the project criterion for outdoor airflow rates.

Pressure Relationships between Zones The relationship of individual spaces to each other in terms of airflow and pollutant transport is of concern in the design and operation of mechanical ventilation systems. Some of these issues are addressed in the BOCA code and the ASHRAE standard. For example, restrooms should be negatively pressurized relative to the occupied space, and the exhaust air from the restrooms should not be recirculated back to the occupied space.

Another aspect of pressure relationships between building zones is based on recommended practices during construction to reduce the potential for indoor air quality problems (Levin 1991). These recommendations are based on current research findings, not on consensus standards or building codes. During construction activity, zones or floors where construction is complete should be isolated from those in which construction is in progress. This can be accomplished by adjusting the supply and exhaust airflow rates of the zones such that air flows from completed zones into the stairways and elevator shafts and from the stairs and elevator shafts into the construction zones. In this way contaminants from construction zones will be hindered from flowing into completed zones. These adjustments can be made using building ventilation systems and/or by installing temporary exhaust systems to exhaust the construction zones directly to the outdoors. In addition, it is sometimes recommended that recently completed spaces be ventilated continuously with maximum levels of outdoor air intake to "flush out" contaminants released from new building materials.

A set of three criteria was established with regards to relative pressurization between zones for this commissioning program. Restrooms should be mechanically exhausted with no recirculation and should be negatively pressurized relative to the occupied space. Occupied spaces should be positively pressurized relative to stairways and elevator shafts during construction. Construction spaces should be negatively pressurized relative to finished spaces.

Pollutants

Carbon Dioxide (CO_2) Carbon dioxide is produced by the occupants of a building and can be a useful indicator of the adequacy of outdoor air ventilation rates per person. ASHRAE Standard 62-1989 provides a recommended maximum CO_2 level of 1,000 ppm (parts per million). According to ASHRAE, this level of CO_2 is not a health risk but is a surrogate for odors produced by humans. However, even if this criterion is met, it does not mean that other contaminants will not reach levels of concern. A CO_2 concentration of 1,000 ppm was selected as the criterion for this project.

Carbon Monoxide (CO) Carbon monoxide is produced by combustion processes associated with activities such as cooking, smoking, and motor vehicle operation. This building has an underground garage, which is a potential source of carbon monoxide for the occupied portion of the building. There are no standards for maximum CO levels for office environments, but other guidelines are available. The U.S. Environmental Protection Agency's (EPA) National Ambient Air Quality Standards contains a CO guideline for outdoor air, and ASHRAE Standard 62-1989 uses this value as a criterion for the acceptability of intake air. According to this criterion, average CO concentrations are not to exceed 9 ppm over an eight-hour period and 35 ppm over a one-hour period. The appendix of ASHRAE Standard 62-1989 contains two other guidelines provided by the World Health Organization (WHO). One guideline is based on eye irritation from passive smoking and gives a level of less than 1.7 ppm as being of limited or no concern and levels greater than 4.4 ppm as being of some concern. The other WHO guideline is based on continuous exposure and lists levels of less than 9.6 ppm as being of limited or no concern and levels greater than 26.2 ppm as being of some concern. Another guideline is in the BOCA National Mechanical Code for establishing maximum recirculation rates for the mechanical ventilation system and indicates an annual average concentration of 17 ppm and a 24-hour average of 26 ppm. The BOCA code does not indicate that these guidelines should not be exceeded indoors, only that they must be met in order to recirculate return air back to the ventilated space.

A maximum CO concentration of 10 ppm was selected for this project based on the continuous exposure level recommended by the World Health Organization. Ambient levels of CO typically do not exceed 2 ppm, except in urban environments. Therefore, if indoor levels of CO exceed 10 ppm, it is probably an indication that there is some source of CO impacting the indoor environment. It could be argued that indoor CO levels lower than 10 ppm could indicate a significant indoor source, but no other guidelines or documentation are available to justify a limit below 10 ppm.

Formaldehyde (HCHO) Formaldehyde is used to produce urea- and phenol-formaldehyde resins, which are then used to make adhesives. Indoor sources of formaldehyde include urea-formaldehyde foam insulation, pressed wood products (particle board, medium-density fiberboard, and interior-grade hardwood plywood), and some fabric treatments. There are no formaldehyde standards available for office space in the U.S., but there is a Department of Housing and Urban Development (HUD) standard for manufactured homes (0.4 ppm) and guidelines from WHO indicating that formaldehyde levels less than 0.05 ppm are of limited or no concern and levels higher than 0.10 ppm are of some concern. A one-week average HCHO concentration of 0.05 ppm was selected as the project criterion.

Particulates Particulates that are less than 10 μm in diameter (referred to as PM 10) are of concern in terms of human health. Guidelines for outdoor air particulate levels are given by the EPA in the National Ambient Air Quality Standards and are provided in ASHRAE Standard 62-1989 as criteria for the acceptability of intake air. The BOCA National Mechanical Code also presents guideline levels for particulates in the ventilation air of a building; however, these guidelines are provided as a means for determining maximum recirculation rates. The BOCA code does not indicate that these guidelines should not be exceeded, only that they must be met in order to recirculate return air back to the ventilated space.

The project criterion of a maximum short-term concentration of 150 $\mu g/m^3$ is based on the National Ambient Air Quality Standards set forth by the EPA. This criterion applies to respirable particulates that are less than or equal to 10 μm in diameter.

Radon Radon is a radioactive gas that can enter a structure through airflow paths in the foundation of a building. Radon decays into other ions (progeny), which can then attach themselves to suspended particulates in the air and be inhaled by humans. ASHRAE Standard 62-1989 contains a guideline for radon based on the EPA guideline of 4 pCi/L for homes. ASHRAE recommends this as a guideline to be used for other buildings until specific guidelines for other occupancies are published by appropriate authorities. The project criterion for radon is also set at 4 pCi/L based on an average concentration determined over about three days.

Volatile Organic Compounds (VOCs) VOCs are compounds that evaporate from products and materials made with organic chemicals. Among many other sources, VOCs are emitted by solvents and adhesives used in construction and by many building materials. Many VOCs can be irritating to humans and some are known to cause adverse health effects. There are no standards for indoor levels of VOCs. However, a tentative set of guidelines for total volatile organic compound (TVOC) concentrations in nonindustrial indoor environments has been suggested based on field investigations and laboratory experiments (Mølhave 1991). These guidelines are very preliminary and are based on a limited amount of research. More research and data are needed to develop a more dependable set of guidelines. This set of suggested guidelines breaks down TVOC levels into four categories of effects on humans: the *comfort range*, in which no irritation is expected (less than 0.2 mg/m^3); the *multifactorial exposure range*, in which irritation and discomfort are possible if other exposures interact (from 0.2 to 3 mg/m^3); the *discomfort range*, in which occupant complaints, probable headaches, and other exposure effects occur if VOC exposure interacts with exposures other than VOCs (between 3 and 25 mg/m^3); and the *toxic exposure range*, in which headaches and additional neurotoxic effects may occur (greater than or equal to 25 mg/m^3).

Based on Mølhave's preliminary guidelines, a guideline maximum TVOC level of 1 mg/m^3 will be used as the project criterion for VOC concentrations. This value falls into the multifactorial exposure range of Mølhave's guideline values of TVOC levels. This criterion for TVOC concentrations neglects the variation in irritancy and health effects among individual volatile organic compounds.

Thermal Comfort—Operative Temperature and Relative Humidity The proper control of temperature and relative humidity (RH) is important to maintain occupant comfort in a building. Thermal comfort is a function of air temperature, relative humidity, radiant temperature, and air speed. ASHRAE Standard 55-1992 (ASHRAE 1992) provides a range of acceptable thermal comfort, referred to as the "comfort zone," based on the dew-point temperature, relative humidity, and operative temperature. Operative temperature is a parameter that takes into account the values of the dry-bulb temperature, radiant temperature, and air speed. The coordinates of the comfort zone are given for both winter and summer conditions in Figure 2 of ASHRAE Standard 55-1992. The project criteria for thermal comfort are based on the coordinates of the comfort zone given in ASHRAE Standard 55-1992.

Test Methods

This section describes the test methods being used to monitor the indoor air quality parameters in each of 11 *zones* of the building, i.e., levels 2 through 10, the daycare center, and the auditorium. These zones are defined as such for the purpose of this study and do not correspond to the zoning of the heating, ventilating, and air-conditioning (HVAC) system. The measurements in this study are "spot" measurements that only provide a one-time value of the measured parameters. Outdoor airflow rates were measured twice in one week in each of the 11 zones, and pollutant levels and thermal comfort parameters were measured once in several locations throughout each zone. Ideally, real-time or at least more frequent measurements would be performed, but the resources required for such an effort were not available.

Outdoor Airflow Rate Outdoor airflow rates to each zone are being measured with two methods, referred to as direct and indirect. The direct method entails performing only velocity traverses of the outdoor air delivery ducts serving each zone with an anemometer. The provision of outdoor air to the "zone" as a whole does not guarantee the proper distribution of outdoor air to individual workstations, but the scope of this program did not provide for such a detailed study of the ventilation system. Ideally, the distribution of outdoor air to individual workstations would be verified under fully occupied conditions (Dols and Persily 1994). These traverses are performed in both the outdoor and make-up air ducts serving an air handler (see Figure 1). The indirect, or multiplicative, method involves the measurement of the supply airflow rate and the percent outdoor air of the supply airstream of each air handler serving the zone. The supply airflow rate is then multiplied by the percent outdoor air intake rate to obtain the outdoor airflow rate. Percent outdoor air intake rates are measured using sulfur hexafluoride (SF_6) as a tracer gas. A small volume of tracer gas is injected into the supply air as it leaves the air handler. After allowing the tracer gas to mix within the zone for about 15 minutes, the tracer gas concentrations of the supply, return, and outdoor airstreams are measured. These concentrations are then used to determine the percent outdoor air intake based on a mass balance of air and tracer gas at the air handler (Persily 1994). The supply airflow rate of the air handler is determined with a velocity traverse of the supply air duct.

Pressure Relationships between Zones The relative pressurization between zones is being evaluated to determine the pressure relationships between zones under different phases of construction and to provide information on possible pollutant transport paths. Pressure relationships between zones are evaluated using smoke tubes to establish the direction of the pressure difference between the zones in question.

Carbon Dioxide Carbon dioxide concentration is measured using portable monitors based on infrared absorption. Samples are taken throughout the occupied space of the zones during occupied hours of the day as well as outdoors. Because CO_2 is generated by building occupants, it is being sampled only after the zones are occupied.

Carbon Monoxide Carbon monoxide concentrations are measured using a portable electrochemical analyzer. Samples are taken at approximately six locations within each zone, in the parking garage, and outdoors during occupied hours.

Formaldehyde Formaldehyde levels are being measured using passive samplers that determine an average concentration over a period of five to seven days. The samplers consist of a glass vial with a sodium bisulfite-treated filter on the bottom. At the beginning of the test period, the cap is removed from the vial at the test site and the formaldehyde is absorbed by the treated filter. At the end of the test period, the cap is placed back onto the vial and the vial is sent to a commercial laboratory for analysis. Samples are taken at two locations within each zone, including some spaces (such as conference rooms) with a potential for a high loading of pressed wood products. During each set of measurements an outdoor air sample is also collected.

Particulates Particulate sampling is being performed using a respirable aerosol mass monitor that collects particulates from 0.01 μm to 10 μm in size. Nonrespirable particles (greater than 10 μm) are separated from the respirable particles, which are then collected on a quartz crystal sensor. This sensor determines the concentration of particulates collected in units of $\mu g/m^3$. Short-term samples (five minutes) are collected at about six locations in each zone.

Radon Radon is being sampled using activated charcoal canisters. These canisters are used to obtain average radon concentrations over a three-day period. The canisters are placed at the sample locations and opened to expose the activated charcoal. After three days, they are resealed and sent to a commercial laboratory for analysis. Results are provided in units of pCi/L. Radon is the only pollutant in the study that will not be measured in one zone at a time. Instead, radon will be measured in every zone, including the garage levels, simultaneously during the last two phases of task 3.

Volatile Organic Compounds VOC samples are being collected using a portable pump to draw air from the sample location through a tube (trap) filled with a sorbent (0.5 g of 35/60 mesh of 2,6-diphenyloxide) that absorbs VOCs from the air. Samples are then analyzed with a gas chromatograph connected to a mass spectrometer (GCMS) with a mass selective detector (MSD). The concentration of TVOCs is then determined from a combined response of all organic compounds found in the sample and compared to a toluene standard to determine the TVOC concentration in mg/m^3. Two samples are taken in the return air plenum just upstream of one of the mechanical rooms serving the test zone. Two outdoor samples are also collected on the roof of the building for each set of measurements.

Temperature Temperature measurements are being made using a portable resistance temperature detector (RTD). Temperature is measured at approximately six locations throughout the test zone to obtain information on the temperature uniformity within each zone.

Relative Humidity Relative humidity is being measured using a portable digital hygrometer employing a thin-film humidity sensor with an accuracy of 2%. The relative humidity is measured in about six locations throughout each zone as well as outdoors, and is measured to obtain information on thermal comfort and uniformity within each zone.

Operative Temperature The operative temperature is being measured using a thermal comfort meter that is specifically designed to determine the operative temperature. These measurements are performed in approximately six locations in each zone but only during phases 2 and 3 of task 3.

TASK 3—IAQ MEASUREMENT RESULTS

Task 3 consists of three phases of IAQ measurements at different phases of construction and occupancy. The first two phases have been completed and the results of phase 1 are presented in this paper. The first phase of task 3 was to perform measurements of the following parameters after completion of the interior buildout of each of the 11 zones: outdoor airflow rate, relative pressurization between zones, formaldehyde, particulates, TVOCs, temperature, and relative humidity. The results of these measurements are presented in Table 2. Where applicable, the criteria to which they are compared are also included in the table. In the case of parameters for which multiple measurements were made in a zone, the value in the table is the average of those measurements. Completion of the interior buildout occurred in stages; therefore, measurements in some zones were performed while construction was in progress in other zones. The measurements were performed in two or three zones over a roughly one-week period. The auditorium was not complete at the time of these measurements. During these measurements, the outdoor air intake fans and the supply air handlers were intended to operate 24 hours a day. However, on several occasions the outdoor air intake fans shut down due to extremely cold weather, sometimes for several days at a time but usually only during the evening.

Outdoor Airflow Rates

The outdoor air delivery rates to 10 of the 11 zones (19 air handlers) were measured and the results are presented in Table 2 along with the design outdoor airflow rates. The measured outdoor airflow rates per person are also given based on the design occupancy. The first row of results for each zone corresponds to the day on which the TVOC samples were collected. During the outdoor airflow measurements, the outdoor air intake dampers were opened and the make-up air dampers were closed; however, there was leakage of outdoor air through the make-up air dampers. Measured outdoor airflow rates to each zone are given for only the outdoor air intake duct (labeled *Intake*) and through both dampers combined (labeled *Total*). Outdoor airflow measurements through the intake dampers were made for zones 4 through 10, and the rates were all higher than the design intake rate with the exception of zone 4. The low airflow rate to this zone occurred because the outdoor air intake rate to one of the air handlers serving the zone was less than 50% of the design value. Almost all the per person outdoor airflow rates based on the intake measurements were at or above the criterion of 10 L/s per person for all of the zones. Leakage rates through the make-up air dampers were mostly between 400 and 800 L/s per zone. Outdoor airflow rates and per person outdoor airflow based on the total delivery rate to each zone were all higher than the design and criterion (ASHRAE Standard 62-1989) intake values, with the exception of the zone 4.

These airflow measurements only provide information at the time at which the measurements were performed. These measurements and other inspections of the ventilation system indicate that the system was not yet being operated as intended. This conclusion is not surprising since the testing and balancing of the system was not complete during this phase of the project. The results do show that the outdoor air intake fans are capable of delivering the design outdoor airflow and meeting the criterion for per person outdoor air delivery; however, some adjustments of the outdoor air delivery rates and the outdoor air fan controls are still required to meet the design goals for the ventilation system.

Pressure Relationships between Zones

Smoke tests were performed to determine the pressure relationships between different zones of the building. The direction of airflow was determined between each zone and the north stairwell, south stairwell, and the elevator shaft. This was done to determine possible paths of pollutant transport between different zones of the building. Generally, air was flowing from the occupiable space into the stairwells and elevator shafts. This is the desired condition since it should minimize the transport of pollutants between the construction and nonconstruction zones of the building. There were occasions when air flowed from a shaft to the occupiable

TABLE 2
Measurement Results

Zone	Test Period	Outdoor Airflow Rate [L/s] Design	Measured Intake	Measured Total	per person Intake	per person Total	TVOC [mg/m^3] Indoor	TVOC [mg/m^3] Outdoor	HCHO [ppm] Indoor	HCHO [ppm] Outdoor	Particles [$\mu g/m^3$]	T [°C]	%RH	Relative Pressurization between Zones: North Stairs	South Stairs	Elevator Shaft
Daycare	12/27/93 - 1/6/94	708	-- --	830 0	-- --	8 * 0	0.59	0.11	0.02	0.02	22	18	15		Lobby -> DCC	Lobby -> Shaft
2	12/27/93 - 1/6/94	1558	--	2590	--	30	0.11	0.11	0.01	0.02	21	22	9	Space -> Stair	Stair -> Space	Shaft -> Lobby
3	12/27/93 - 1/6/94	1558	--	3940	--	44	0.44	0.11	0.03	0.02	12	22	11	Space -> Stair	Space -> Stair	Shaft -> Lobby
4	11/22/93 - 11/29/93	3210	2180 1830 2280	2790 2490 2900	15 13 16	19 17 20	1.21	0.07	0.03	0.04	247	23	--	Space -> Stair	Space -> Stair	Lobby -> Shaft
5	11/22/93 - 11/29/93	1558	2430 3610	3450 3610	29 42	41 42	0.83	0.07	0.02	0.04	27	22	--	Space -> Stair	Space -> Stair	Lobby -> Shaft
6	11/29/93 - 12/6/93	1558	1720 1710	2290 2290	10 9	13 13	0.53	0.09	0.02	0.04	20	23	22	Space -> Stair	Space -> Stair	Lobby -> Shaft
7	11/29/93 - 12/6/93	1558	3260 3110	4120 3970	18 17	22 22	0.28	0.09	0.03	0.04	17	21	24	Space -> Stair	Space -> Stair	Lobby -> Shaft
8	12/13/93 - 12/22/93	1558	2130 2300	2620 2860	10 11	13 14	0.26	0.05	0.05	0.04	12	21	12	Space -> Stair	Space -> Stair	Lobby -> Shaft
9	12/13/93 - 12/22/93	1558	2050 2310	2750 2890	10 12	14 15	0.64	0.05	0.04	0.04	13	21	12	Space -> Stair	Space -> Stair	Lobby -> Shaft
10	12/13/93 - 12/22/93	1558	2180 2490	2880 3100	11 13	15 16	0.68	0.05	0.05	0.04	13	20	14	Space -> Stair	Space -> Stair	Lobby -> Shaft
Criterion						10	1.00		0.05		150					

* Outdoor air intake criterion for the daycare center is 8 L/s per person

space, but this was usually due to some atypical situation such as one of the outdoor air fans being off or a door to the roof being left open.

Formaldehyde

All indoor formaldehyde concentrations were less than or equal to the project criterion of 0.05 ppm. The outdoor levels were between 0.02 and 0.04 ppm. In most cases the indoor levels were less than the outdoor levels by about 0.01 ppm, but this difference is similar in magnitude to the uncertainty in the concentration measurements.

Particulates

In all but one case, the concentrations of particulates were between 5 and 30 $\mu g/m^3$, which is well below the criterion of 150 $\mu g/m^3$. Concentrations between 100 and 400 $\mu g/m^3$ were measured on the fourth floor after the interior buildout was complete on the floor. These elevated levels were due to construction activities that were in progress on the fourth floor at the time of the measurements.

Volatile Organic Compounds

The measured TVOC concentrations in all but the fourth-floor zone were less than the criterion of 1.0 mg/m^3, and most values were less than 0.7 mg/m^3. The fourth and fifth floors were the first floors to be tested and they also had the highest TVOC concentrations. The ventilation system was not being run continuously until only the day before these tests were performed, and even then the systems were not running as intended due to testing of fire/smoke control systems. In addition, as mentioned earlier, construction activities were in progress on the fourth floor at the time of the measurements.

Temperature and Relative Humidity

Temperature and relative humidity were measured at several locations throughout each completed zone, and the average temperature and relative humidity for each zone are presented in Table 2. Temperatures ranged from 16°C to 24°C and relative humidity ranged between 8% and 24%. The HVAC system was not running as designed at this point of construction, and the thermal loads in the zones were not representative of occupancy. Therefore, these results are not useful for evaluating the ability of the system to provide acceptable thermal comfort, but only as supporting data for the contaminant measurements. The low levels of humidity are not surprising because these measurements were performed during the winter and the HVAC system does not have the capability for humidification. The humidity measurements should be repeated under occupied conditions during the winter.

CONCLUSIONS

The design airflow rates of the mechanical ventilation system were compared to both the BOCA Mechanical Code, upon which the ventilation system design was based, and ASHRAE Standard 62-1989. The design ventilation rates conform with the BOCA code and in some cases exceed the BOCA requirements. The design outdoor airflow rates are slightly below the ASHRAE recommendations in several zones and well above ASHRAE recommendations in others, but overall the system appears to be capable of providing outdoor airflow rates to all zones of the building that would comply with ASHRAE Standard 62-1989. The design exhaust airflow rates of all restrooms are greater than the supply airflow rates, as required by both BOCA and ASHRAE. Design outdoor airflow rates to the restrooms exceed the BOCA requirements but do not meet the recommendations of ASHRAE Standard 62-1989.

A set of IAQ commissioning criteria was developed, and the results of the first of three phases of testing in the building were described. The parameters measured during the first round of testing were outdoor airflow rates, relative pressurization between zones, formaldehyde concentrations, particulate concentrations, total volatile organic compound concentrations, temperature, and relative humidity. Total outdoor airflow rates to all zones were above design flow rates with the exception of zone 4; however, the per person ventilation rates based on the total outdoor air delivery rate and design occupancies were all above the criterion of 10 L/s per person. Generally, each zone was positively pressurized relative to the stairs and elevator shafts, with a few exceptions on isolated occasions. Formaldehyde concentrations were at or below the criterion of 0.05 ppm in every zone and were not more than 0.02 ppm greater than the outdoor concentration. Particulate concentrations were generally between 5 and 30 $\mu g/m^3$, which is well below the criterion of 150 $\mu g/m^3$. Total volatile organic concentrations were below the criterion of 1.0 mg/m^3 in all zones but the fourth floor, in which the concentration was approximately 1.2 mg/m^3. Finally, temperature and relative humidity measurements ranged from 16°C to 24°C and 8% to 24% RH, respectively.

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